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THEORETICAL ASPECTS OF PHOTOVOLTAIC CELL CrERATION

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THEORETICAL ASPECTS OF PHOTOVOLTAIC CELL OPERATION

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1. INTRODUCTION

?The photovoltaic effect was first discovered in a liguia solution in 1839. In 1876 the discovery of the photovoltaic effect in solid material followed when selenium was used to convert about 1 percent of sunlight into electricity. The developnent of semiconductor technology in the carly 1940s contributed to new advances in the photovoltaic field. The feasibility of s photovoltaic device made of pure silicon wes demonstrated by Bell Telephone Laboratories in

the United States in 1941. However, the first practical solar cell was not introduced until 1953 in response to the needs of the space program, ?These firet solar photovoltaic cells were made of single crystal silicon and showed about ? percent efficiency.

Single-crystal silicon is the most commonly used material in the hanufacture of solar cells today. The present high costs associa- ted with the manufacture of single-crystal silicon has prompted in= tensified research on polyeryetalline and amorphous silicon cells to reduce the cells? cost, this cost reduction can be accomplished by using lower purity silicon material, less expensive refining pro- cesses and lece silicon for cach cell.? Also during the last few years, thin film techniques and concentrators have been used to achieve this goal. In addition to silicon base materials, non-sili~ Gon based materials nave been used for photovoltaic cells. ?This group includes cadmium sulfide, cuprous oxides and gallium arsen- ide, as well as other more conplex compounds [1]. ?These new tech- hagues ?and manufacturing technologies demand theoretical and exper- imental studies of various effects taking place during photo-current generation inva cell. Thue, understanding the basic aspects of a Photovoltaic cell's Speraticn is an essential element of the re- Search and development taking place in the photovoltaic area today.

2. rHorovoutarc EFFECT

A photovoltaic cell consists of two layers of semiconductor mater- fais, a p> and n-layer, put together in a sandwich configuration (see'Fig. 1)

?The sunlight photons having the energy shown by equation (2)

Ee nv e a

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where

E = energy of photon

V = frequency Of Light

h = Planck's conetant

E,= band gap eneray of the semiconductor material

can free electrons from their covalent bond* in the cell material

when striking the photovoltaic cel? surface. Different photovoltaic

celi materials have different band gap energies at which electrons

are freed. For silicon, the band gap energy value ic fg ° 1.J eV
{at 300°K) so that light with a wavelength ensiler than?1.13 um
frees electrons fron their covalent bons. For gallium arsenide,
the Eg = 1.4 eV; other photovoltaic materials have band gap enersy
fron 8.¢ to 2.6 eV, For outer space (AMO) the best photovoltaic
material is one with a band gap at 1.6 eV. Because of changes an
the solar energy spectrum ac sunlight pastes throwsh the atmosphere
at sea level (AMI), the predicted optimum 1les between 1.25 and 1.3e¥.

If an electron is excited across the gap, it leaves a vacancy in the
valence band** which is referred to as a ?hole.? an electron near

a hole can junp in to fill that vacancy, lesving @ new hole au the
Place that ie had occupied, and that vacancy can in'turn be files

by another electron, and so on. th a photovoltaic eell the current
45 then actually cairied by electrons moving in relays, but it can

equally be pictured as a flow of positively charged heles moving

in the opposite direction during the exposure of @ cell to sunlight.

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FIGUKE 1, P=N junction photovoltaic cell.

selection-pair bond whicn binds the crystal firmly toyether.

**Silicon has four valence electrons, all of which are part of

covalent bond.

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?The free electrons are the msjority carriers in the n-region; the holes, in'the peregion. Tho Auwer of majoriey Carriers) in'goneral

15 determined by dopant* concentration and not very sensitive to either thermal or light excitation. But the nunber of minority

carriers ?holes in the n-region and electrons in the p-region ? is very sensitive to both thersal and light exestation, and this sensitivity has strong effects on the operation of a solar cell.

The flow of thermally generated minority carriers in a solar cell in darkness is called a ?dark drift current." This current is op- posite in direction to the photocurrent and it tends to short the Gevice. ?Ihe dark crift current, or as it is sometimes called the Saturation current, is balanced by an opposing flow of charge car~ riers across the jinction®® ? a "back iffusion" of majority car- riers (electrons crossing from n-region to p-region, and holes cros- sing fron p-regicn ts n-region), flowing against the electrostatic potential established by the junction. ?These two opposing currents Gre equal $n magnitude and asa result, a p-n junction in the dark Produces no net curzent.

hen sunlight fails on a pen junction photovoltaic cel! while it is short-circuited, the magnitude of the electrostatic potential re~ mains basically the sane as it was in darkness, although additional minority carriers are forned Ly photons absorbéd in both n-regions and p-regions and are swept across the junction. The flow of these Binority carriers is in the same direction as the dark drift cur- rent, and is a ret current flow called the photogenerated short- circuit current I... ?The photogenerated current in an external load RL. y(see Pil! 1) is proportional to the intensity of sunlight. ?the sak@Photovoltaic cell in sunlight, but under an open-circuit condition, cannot develep a net current flowy instead, the coll achieves an egual internal flow of majority and minority carriers Seross the junction Ly reducing the electrostatic potential from its original value. This decrease in barrier potential causes a voltage of the same magnitude across the onen-circust terminals:

of the cell, which is called the epen-eireust voltage V,,

PHOLOVOLTALE CELL OPERATI

Whon an external load is connected acruss a photovoltaic cell sub-

jected to sunlight exposure, electric current will flow and useful

power will be delivered, The voltage across the cell will be re~

Suced from the open-circuit value, nence the cell net current will

be the diiference between the photogenerated-current J, and the

cell dark current I. Thus a

Joy - oy «

Figure 2 shows the J-V characteristic for a photovoltaic cell with

*A silicon crystal with added phosphorus dopant is called n-type (nequtive) silicon and with a@ded baron is called p-type (posi=

?his is a line which @ivides n-type trom p-type silicon and which

establishes the prsition of the electric potential Lorrie essen=

tia. to the operation of @ photovoltaic celle

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FIGURE 2. J-V characteristics for a photovoltaic cell under vari-

able load conditions.

the shift in J-v curve for when the load is varied. This curve is

basically the diode J-v curve shifted down the current axis by the

amount of the photocurrent. In the forward bias condition, the

Current increases exponentially with applied voltages

Using the above relationship, the limiting behavior of any photovoltaic cell can be predicted by determining J, and J) values. Ex-

perimentally, the dark current value can be obtained By applying a

large negative voltage across the junction

ven a photovoltaic cell operates under short circuit conditions

nye 8 ang a's dec «ahort Ciscult cutfentys the net cursents se

through" the vena, (ace Vig. 1) can be determines trae the? #oftou

fing: sguat ont

a)

Silumination current

dark current

voltage across load

In the case of an open circuit operation Rr eo and V, = Voge where

Yoo = HE + 1). Power output can be expressed as equal t vueR a

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For each photovoltaic cell at a given illumination intensity, there

Will be a point where maximun power is delivered to the load and the

cel} operates at or near this point. ?The condition for maximum

power is

er,

geo ©

?The photovoltaic cell maximum power is defined as:

Poa 7 On

?max ~ ap * mp 46)

The voltage Vmp at maximum power output is related to the open cir-

cuit voltage Ue. by the following expression:

2 np 3 pp Woe

exp Sgt x (GgBP + a) = exp 259 om

and

R, we.

?une «©

ao5%

where A is the area of the photovoltaic cell.

Another parameter related to open circuit voltage is called the voltage factor VF and is defined as the ratio of V.. to the band gap enersy Ey.

Maximum power which can be delivered by @ photovoltaic cell is represented by the largest rectangle which can be contained under the illuminated J-V curve of the cell (see Fig. 2). The Voltage Uap and the current Jno defining this rectancle describes another parameter which is called a fill factor FF.

Van * 9,

rr = ob 7 Sep ?

Toe * 9,

where J. Jg.. the 111 factor accounts for all the effects acting

on the Bhape®S! the dark current cu ve. The maximum power obtained

from a pen junction piiotoveltave cell depends upon Voor Sec and FF

values. oe -

Finally, the conversion efficiency of a photovoltaic cell is defined

as the ratio of cell electrical power output to solar power inputs

Thus, the theoretical conversion efficiency of the photovoltaic cell

at the maxinun power pont is equal to.

Ve, 2 By ox VF x FP xo

op op

nput? Bower? > a0)

Because of the low power density of sunlight and the Limited conver-

Sion efficsencies, today's photovoltaic cells can generate only up

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to 250 watts per square meter. Figure 3 shows the theoretical con-

version efficiencies of various photovoltaic cells.

§

max(PERCENT)

3

o 05 10 15 20 25

ENERGY GAP (ev)

FIGURE 3. Theoretical conversion efficiency vs energy cap values

for various photovoltaic celle (2)

PARAMETERS AFFECTING CELL EFFICIENCY

4.1 open Circuit voltage

Open circuit voltage is one of the parameters which affects the efficiency of @ photovoltaic cell; a high value is desirable,

Noe * ay

at room tenperature and with a, >> 3,

a

Noe * 90878.» toss a2)

Voge Can be maximized by minimizing 3,

Therefore it is important to consider the values affecting Ip.

For a monocrystal it can be shown that:

an

where ty and Np are minority carrier concentration values inn and

Players, and Ly and lp are muority carrier diffusion length in

A and p layers? Fespectively.

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aay

as)

where D, and D, are diffusion coefficients of minority carriers in

n and pPayers"and T, and T, are minority carrier lifetimes in a

and p layer: =

In connercially processed cells a short diffusion length is observed

Since @ large number of generated carriers recombine on the back

surface of a cell.

no xa, ae

ay

Where wp and u, are mobilities of minority carriers in the n and p

layers Fespectively.

For pon junction with a.c< p, the value of 9, will be:

D

as)

With @ large impurity concentration of tne order of 10)%/em, the minority carrier's lifetime is 164 ysec and this results in ¢ very

large minority carrier diffusion length. The minority Iifetine. in

the base layer, whict: depends on the purity and perfection of the

base material, is one of the ost important parameters affecting

the cell efficiency.

In consequence of the above, it can be shown that for a silicon mon

ecrystal cell of p-n ?type the value of tne open circuit voltage

at Foon temperature is:

0.062 exp 39 t,

0.0575 x log {x x (0062 exp 28 ¥

Yoo 5 x Log {a x L pe

?The equation (19) shows that the larger the band gap the largor the

open circuit voltage [3]. For a given band gat material, the resis-

tivity of the materiol should be low; the carriors should have a

Jow mobility and high minority carrier lifetimes Furthermore, the

net current? should be large fora high Vic

as)

In a polycrystelline silicon coll the V_. depends on the grain size,

the lorucr the grain size the larger enopen circuit voltage as

shown in Figure 4. he grain size can vary from 1 um to several

millineters or even centimeters.

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Current, smavem?

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Voltoge, Voe Volts

FIGURE 4. Voc dependence on the grain size for polycrystalline and

single crystal silicon [3].

4.2 short Circuit current

The short circuit current can be expressed by the following rela-

tionshi

(20)

where Lis the Light absorption coefficient.

4.3. Shunt and Series Resistance

Photovoltaic cells may have @ shunt resistance Ry, a8 a result of

manufacturing and may nave a series resistance RS'due in large part to

the resistance to conduction in the thin diffused layer on the top

of the cell. The internal voltage drop in a cell can usually be

minimized by the proper design of the metalization resulting in the

conductivity of the material to be such that R. is often asguned to

be equal to zero. .

Figure § shows the equivalent circuit diagram of a p-n junction without x and Ho, and Pig. 6 shows the equivalent circuit of a

photovoltiic celf?with Rand Ro. Tt can be shown that as a re=

sult of the series resisfance afl? the shunt resistance, the J-V

Felationship takes the following form:

ap-3 vor any

Rea ee

$x werny = ane +n en

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FIGURE 5. Equivalent circuit

cell without Ry and Rp.

FIGURE 6. Equivalent circuit dia

ram for a p-n junction photovoltaic

cell with Ry and Roy.

regxa

A= brea of photovoltaic cel!.

Increasing values of 2, and} makes the fill factor decrease in

yelve and for high efficiencil of a photovoltaic cel, Loth Ry and

fy, SPOU1E be sndd

4.4 Current and Voltage Losse:

?The most effective crystalline silicon laboratory cells use a p-n

homojunction and convert up to 19 percent of the energy in incident

Sunlight into electricity at 20°C and AMO.? In theory, silicon p=n

junction pliotovoltaic cells can convert a maximun of about 22 per=

cent of encray in AMO sunlight into electricity. However, 73 per=

cent of the eneray in sunlight i lost due to factors intrineic to the cell itself

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Resistance losses. Resistance losses lover a cell's output voltage and enhancé the chance of recombination of charges, reducing net electric current. Resistance losses occur predominantly in the bulk of the base material, in the top surface layer, and at the in-terface between the cell and the electric contacts ieading to an external circuit.

Recombination of charges. Recombination of charges results from the intrinsic restetarce in the cell and feade te current and vel tage losses. When this occurs charge mobilities are reduced and the likelihood of recombination caused by empty bonds from impuri~ ties or defects (fractures), which can capture free electrons oF holes increases. This indirect recombination ie dominant. The Surface of a ceil can be the site of much recombination.

In polycrystalline silicon cells, the recombination per unit volume is inversely proportional to the'grain size and depends on the dif fusion potential. This causes the minority carrier lifetime to do-crease with grain size.

Low_and high temperature losses. Low-temperature losses occur as Eonpernture Yells, siice thermal encrgy le less able eo free charge carriers fron either dopant atons or intrinsic silicon; mobility of

charge carriers drops and dopants behave as if they were normal si1-icon atoms.

When the temperature of a photovoltaic cell rises, the cell conver-sion efficiency decreases as illustrates in Figure 7. This decrease Occurs because the additional thermal energy increases the thermally generated dark drift current.

Reflection losses. Reflection losses of sunlight that strikes Photovoltare celi can be reduced below 5 percent by applying anti-Feflective coating or texturing the surface. Normal, untreated silicon reflects from 36 to 70 percent of sunlight which strikes it depending on the wavelength as shown in Pigure &

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* 100 200, 300 400

Semiconductor Temperature (°C)

various photovoltaic cells 14]

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FIGURE 8. Variation of reflectivity with wavelength for silicon!5}

Absorption of photons. Absorption of photons by the cell material

Ts another Factor influencing? the coal merit meth Set intensity

Of photons at depth x can be presented by the following equatior

$1 = T, \exp(-0x)$ (22)

where:

1, = intensity of photons at material surface

& = absorption coefficient of material.

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58

= ani

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= amo

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' 10 100 1000

?Thleknens of silicon Cum)

FIGURE 9. Absorntion effect for silicon exposed to sunlight ot AMO and aM) (6).

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It is clear that electron-hole ceneration decreases exponentially with distance into the semiconductor. The absorption effect for Silicon exposed to AMO and AM! sunlight is shown in Figure 9. The excess of energy which is not absorbed by the material is lost as heat. In the case of silicon all photons with wavelength 1.13ym are lost. These losses can be in the range of 30 percent. Pig= ure 10 shows the variation of the absorption coefficent with inci~ dent sunlight energy for various photovoltaic cells.

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LENERG YAN) (ase sone)

FICURE 10. Variation of absorption coefficient with the incident energy Of sunlight for various photoveltase cells [6].

5. concLuszoNs

The various parameters discussed above have a significant impact on photovoltaic cell operation and performance. These parameters could be divided into mechanical, electrical, optical and thermal ones. The role of sone of ther during the cell's operation is already well known, others are still being studied. bye to ehis intensive experimental research and theoretical studies, significant progress has been made in better understanding the various theoretical aspects of a photovoltaie cell's operation. Becuuse of this, and the use of a new generation of cells and improved production technology, an increase in the officiency of crystalline silicon cells from?14 percent to 19 percent occurred. This was accompanied by @ decrease in cost by more than half during the last decade of photovoltaic generated electricity, fron about $20 per peak watt in 1976 to S7=510 per peak watt today. in the same period, the

worldwide production of photovoltaic cells increase? from?0.45 MW,

to over 25 Mi, signifying remarkable market penetration and the

large use potEntial of phatoveltaic cells.

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